Abstract

The Mississippian section of the Mid-Continent has been an exploration target for the oil and gas industry for 90 years. Hydrocarbons have been economically produced from thousands of vertical wells targeting multiple productive facies with log porosity values ranging from 2% to 48%. In 2003, Tulsa-based Ceja Corporation initiated drilling program utilizing horizontal drilling to exploit seismically identified high porosity (>35%) Mississippian tripolite. Through 2009 more than 20 horizontal wells were successfully drilled and completed, setting in motion the hugely extensive Mississippi Lime Play of the Mid-Continent. In 2009 Spyglass Energy Group drilled the Shaw 1A-8H, one of the earliest horizontal well east of the Nemaha Ridge targeting the low porosity (2-6%) Mississippian; the results of which set in motion the assembling of one of the largest acreage positions in the play. Spyglass Energy Group, led by explorationist Charles Wickstrom, has been at the forefront in pioneering the play, taking it from arm-waving to visualization to exploration to full exploitation.

The Mississippi Lime Play is unique in the spectrum of newly defined “Unconventional Reservoirs” in that it encompasses multiple reservoirs of highly varying petrophysical parameters which are commonly stacked or laterally adjacent to one another.
This leads to many misunderstandings of the section. The variability of the section, coupled with the high-fluid-volume production has led to yet another paradigm shift in how the industry interprets reservoir objectives in horizontal carbonate plays. Geologists utilizing fresh eyes on new data while rediscovering the monumental works published throughout the 1900s are on the cusp of cracking the many codes held tight in this dynamic geological section.

**Selected References**


Mississippi Lime: Kinematics of a Play

Structure, Reservoir Characterization and Production Performance of the Horizontal Mississippian Play

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Presentation

• Historical perspective
• Regional framework
• Key play elements
  – Trap dynamics
  – Infrastructure
  – Reservoir geology
  – Stimulation
  – Production results
The Mississippi Play is Huge

Elm Coulee Field
Bakken Formation
~5,000 producing wells
12 million acres

Mississippian Lime Play
Area of Leasing
~1,000 wells drilled
30 million acres

Newark East Field
Barnett Shale
~16,000 producing wells
3 million acres
Historical Perspective

A special problem that we have been dealing with in the last few years is the one where we are concerned about the variation in the fluid levels within what we identify as a single reservoir. What I am referring to is the fact that we can have the following fluid levels in a particular well –

- Gas, Oil, Water;
- Then just Gas and Water;
- Then Oil, Water;
- Then just Oil;
- Then just Gas;
- Then just Gas and Water;
- And then just Water;
- then another zone back to Oil or Gas. We may not have this particular sequence in any one well, but we may have any kind of sequence such as this one.
Historical Perspective

• Preliminary Report on the Lead and Zinc of Oklahoma – OGS Bulletin 9, 1912
• Fauna of the So-Called Boone Chert, USGS Bulletin 595
• The Oil and Gas of Geology of the Foraker Quadrangle, Osage County, OK, USGS Bulletin 641-B, 1916
• Structure and Oil and Gas Resources of the Osage Reservation, Oklahoma, USGS Bulletin 686, 1922
• Helium Bearing Natural Gas, USGS Professional Paper 121, 1921
• Oil and Gas in Oklahoma, OGS 1930
• Symposium on the Mississippian of Oklahoma and Kansas, TGS Digest Volume 27, 1959
• Mississippian Rocks in Eastern Kansas, Proceedings of the 6th Symposium on Geology, Oklahoma Univ. 1957
• Hydrocarbon Accumulation in the “Meramec-Osage” (Mississippian) Rocks, Sooner Trend, Northwest Central Oklahoma, AAPG Bulletin v. 59, 1975
• Geology and Ore Deposits of the Picher Field Oklahoma and Kansas, Geological Survey Professional Paper 588, 1970
• Mississippian Trend Garfield, Major and Alfalfa Counties Oklahoma, The Western Company, 1965
The Woodford Shale was the source for much of the hydrocarbons produced in the Anadarko and Arkoma basins.

- The deep Anadarko basin produced gas-weighted hydrocarbons.
- The Arkoma Basin was shallower and produced oil-weighted volumes.
Arbuckle Structure – East of Nemaha Ridge

Gatewood 1970
Pre-1960
1960-1970

Map showing population density with locations of cities and towns.
2009 - Present
Geological History of Mississippian Reservoirs of OK and KS

- Fine-grained carbonate sands deposited on ramp
- Early diagenetic chert
  - Preferential replacement based on depositional facies (even low-energy deposition is differentiated by grain size across a spectrum)
- Proto-Ouachita Transpressional Tectonics
- Mississippian – Pennsylvanian Unconformity
  - Meteoric impact greatest on pre-existing tectonic-weakened lineaments
- Deposition of Penn Shales
- Continued wrenching of NE Oklahoma – Cracking of the brittle section
- Hydrothermal fluids of unknown origin move laterally through section
  - Tripolization by dissolution of lime
  - Hydrocarbon Filling of traps – World's largest stratigraphic trap?
- Ozark Uplift
- Reversal of dip from west to the east
  - Leak-off of hydrocarbon in high porosity traps
- Hydrocarbon Refill of traps
- Breaching of the reservoir
- Extensional faulting and fracturing due to removal of overburden
- Water moves through the system sweeping higher porosity lithologies
Mechanical Infrastructure and Knowledge Base

• Operational capability
• Water for stimulation
• Disposal capacity for produced fluids
• Power to run lift
Reservoir Geology

Multiple Reservoir Systems
Conventional – Semi-Convention - Unconventional

Unconventional
*Un-Altered*

- 2-6% Porosity
- Massive Stimulation
- Low Natural Deliverability

Semi-Conventional
*Altered*

- 15-20% Porosity
- Stimulation Required
- Medium Deliverability

Conventional
*Highly Altered*

- 35-48% Porosity
- No Stimulation
- High Natural Deliverability

Sweep Efficiency of Hydrological System
*Increases with Porosity*
Reservoir Geology

- Porosity System
  - Unaltered Osage A and B
    - Interbedded Chert and Lime
    - Dense “Matrix” Porosity 1-4%
    - Permeability Values 0.1 to 0.5 md
    - Bed-Boundary Porosity System
      - “True Matrix Porosity”
    - Micro-Porosity – Methane Storage
  - Altered Osage A and B
    - Porosity values 6 – 18%
    - Permeability .05 to 8 md
  - Highly Altered Osage A and B
    - Porosity Values 35 – 42%
    - Permeability Values 0.2 to 20 md

- Fracture System
  - Mega-Fractures – Seismically Defined, Compaction and Tectonic Origins
  - Bed- Bound Fractures – Extensive and dominant in beds with high SiO2
  - Micro-Fracture
Reservoir Geology

- Mississippian Limestone
- Woodford Shale
- Simpson Group
- Arbuckle Group
- Reagan Sandstone
- Granite-Rhyolite Groups

- Oswego Limestone
- Verdigris Sandstone
- Skinner Sandstone
- Pink Sandstone
- Red Fork Sandstone
Reservoir Geology

Osage A
– Unaltered
Silicified Limestone
*High Diagenetic Susceptibility*

Osage B
– Unaltered
Interbedded Chert and Lime
*Low Diagenetic Susceptibility*

Kinderhook Limestone
Mississippian Reservoirs of Northeast Oklahoma

Osage A – Altered
High Degree Diagenetic Susceptibility

Osage B – Unaltered

Kinderhook Limestone
Osage A – Highly Altered

Osage B – Unaltered

Kinderhook Limestone
Image Log Fracture Quantification – Shattered Rock

- 2350’ of lateral interpreted
- 1591 open natural fractures
- Fracture Density – 10 / ft
- Strike N 70 E
Chat Core Photo (2895 – 2913)
Chat Core Photo (2913 – 2931)
3D seismic shows evidence of extensive wrenched terrain. Diagenetic overprint too great and spatial density of wells too sparse to recognize strike slip fault systems.
MississippSeismic “Chat” Stratigraphy
The Tri-State host rock is Mississippian chert breccias and tripolites in a horst-and-graben terrain.

3500’

Geological Survey Professional Paper 588
East West seismic section – Length eight miles
Structure: Seismic
Reservoir Stimulation

• Conventional (35 – 48% Porosity)
  – Open Hole No Stimulation

• Unconventional (4-8% Porosity)
  – Massive Stimulation
  – Possible to UNDERSTIMULATE

• Semiconventional (12-25% Porosity)
  – Possible to OVERSTIMULATE
Conventional Stimulation
Benjamin 4H
Sec 10 T25N R3E
First Production February 2003
Cumulative Production 152,00 BOE (89% Oil)
EUR 183,000 BOE
Williams 3H
Sec 3 T25N R4E
First Production June 2006
Cumulative Production 176,200 BOE (89% Oil)
EUR 257,000 BOE
Lenker 6H
Sec 5 T25N R5E
First Production April 2006
Cumulative Oil Production 110,000 BOE (88% Oil)
EUR > 200,000 BOE
Unconventional Stimulation

- 400’ Stage
- Four 5-Foot Perf Clusters
- Six Shots Per Foot
- 120 Shots per stage
- 5000 to 10,000 BW
- 30K # to 60K # Sand (0.10 # per gal max)
- 160 Bio-Ball Sealers dropped in sub-stages
  - Good Ball Action
Osage B Unaltered – 50 BPM vs. 80 BPM

Hunka 1A (90 BPM) vs. Hunka 3A (50 BPM)

Hunka 1A - Four 6' Clusters, 8 spf, 5K BW, 30K# 40/70 Sand, 234 Ball Sealers, 80 BPM
Hunka 3A - Four 6' Clusters, 6 spf, 5K BW, 30K# 20/40 Sand, 195 Ball Sealers, 50 BPM
Osage B – Unaltered – 5K BW vs. 10K BW

Hunka 1A (90 BPM) vs. Hunk 3A (50 BPM) vs. Shaw 1A (55 BPM)

Hunka 1A - Four 6' Clusters, 6 SPF, 5K BW, 30K# 40/70 Sand, 234 Ball Sealers, 60 BPM
Hunka 3A - Four 6' Clusters, 6 SPF, 5K BW, 30K# 20/40 Sand, 195 Ball Sealers, 50 BPM
Shaw 1A - Four 5' Clusters, 6 SPF, 10K BW, 60K# Sand, 180 Ball Sealers, 55 BPM
EUR 159,000 BO – 1200’ Lateral
To-Op-Pe 1A-4H
Stage Map
9 Stage
400’ Interval
Initial velocity model was constructed from client provided gamma-ray and dipole sonic. The model was further refined with perf-timing measurements and error reducing optimizations on the perforation locations.
To-Op-Pe 1A-4H – Project Setup - Side View
• Fracture Azimuth ~N70°E
• Average Half Length ~850’
• Average Frac Width ~250’

500’ grid spacing

Looking Down

To-Op-Pe 2A-4 SWD

To-Op-Pe 1A-4H

To-Op-Pe 1A-4H – Plan View
500’ grid spacing

- Average Frac Height ~360’
- Downward growth through the Woodford

Looking West

Checkerboard
Big Lime
Oswego
Mississippian
Woodford

4/26/2012 1:11:34 PM
TO-OP-PE 1A-4H
Surf Press [Csg] 1035.6 psi
Slurry Flow Rate 79.9 bcpm
Proppent Conc 0.4 spg
To-Op-Pe 1A-4H – Edge View

500’ grid spacing

Looking North

Checkerboard
Big Lime
Oswego
Mississippian
Woodford
To-Op-Pe 1A-4H – 2D Depth View

Map View
Relative to TO-OP-PE 1A-4H

Profile View - Looking N87°W
Relative to TO-OP-PE 1A-4H

[Graph showing depth view with various data points and measurements]

4/26/2012 1:11:34 PM
Central Daylight Time

TO-OP-PE 1A-4H
Surf Press [Csg] 453.6 psi
Slurry Flow Rate 72.9 bpm
Proppant Conc 0.4 ppg
Events 1 TO-OP-PE 1A-4H
Stage 1
Half Length vs Time
81 BPM Average, 3620 BBL Slickwater
Stage 5
Half Length vs Time
80 BPM Average, 6760 BBL Slickwater

Distance along the fracture azimuth (ft) vs Stage Elapsed Time (min)
Stage 3
Half Length vs Time
80 BPM Average, 10849 BBL Slickwater
Conclusions

• This play is about water
  – high-fluid-volume play
• Variable reservoir requires thoughtful stimulation design
  – Understand the rock you are stimulating
• Standing on the shoulders of giants
  – Many of the answers being sought were asked and answered last century
Acknowledgements

Charles Wickstrom – Spyglass Energy Group
Michael Graves
Nadel and Gussman
Jim Adelson
Steve Heyman
Dennis Webb
Wayne Porter
Steve Tilley
Edith Wilson
J. P. Dick
Al Siemens
Sal Mazzulo
Ralph Davis
Walt Manger
Doy Zachry